(54) Title: GCIB SIZE DIAGNOSTICS AND WORKPIECE PROCESSING
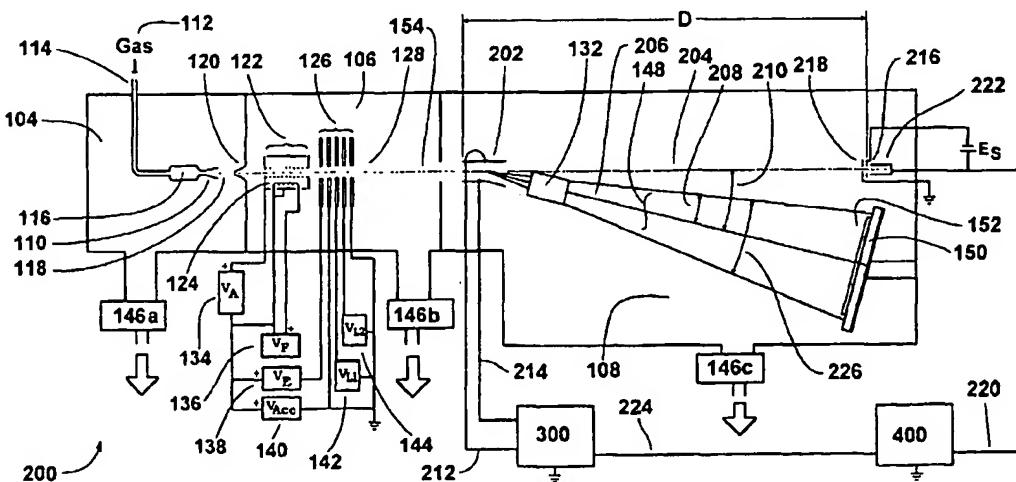
(57) Abstract: Method and apparatus for measuring distribution of cluster ion sizes in a gas cluster ion beam "GCIB" (154) and for determining mass distribution and mass flow of cluster ions without magnetic or electrostatic mass analysis. A Faraday enclosure (222) as part of a time of flight mass analysis unit (400) monitors cluster ion size distribution.

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GGIB SIZE DIAGNOSTICS AND WORKPIECE PROCESSING

BACKGROUND OF THE INVENTION

This invention relates generally to the measurement of the size distribution of gas clusters in gas cluster ion beams, and, more particularly to apparatus and methods for the measurement of the size distribution of gas clusters concurrently with workpiece processing.

The use of a gas cluster ion beam (GCIB) for etching, cleaning, and smoothing of material surfaces is known (see for example, US patent 5,814,194, Deguchi et al.) in the art. For purposes of this discussion, gas clusters are nano-sized aggregates of materials that are gaseous under conditions of standard temperature and pressure. Such clusters typically consist of aggregates of from a few to several thousand molecules loosely bound to form the cluster. Such clusters can be ionized by electron bombardment or other means, permitting them to be formed into directed beams of known and controllable energy. The larger sized clusters are the most useful because of their ability to carry substantial energy per cluster ion, while yet having only modest energy per molecule. The clusters disintegrate on impact, with each individual molecule carrying only a small fraction of the total cluster energy. Consequently the impact effects of large clusters are substantial, but are limited to a very shallow surface region. This makes ion clusters effective for a variety of surface modification processes, without the tendency to produce deeper subsurface damage characteristic of monomer ion beam processing.

Means for creation of and acceleration of such GCIB's are described in the reference (US 5,814,194) previously cited. Presently available ion cluster sources produce clusters ions having a wide distribution of sizes, N (where N = the number of molecules in each cluster - in the case of monatomic gases, an atom of the monatomic gas will be referred to as a molecule and an ionized atom of such a

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monatomic gas will be referred to as a molecular ion throughout this discussion).

To a first order approximation, the surface modification effects of an energetic cluster is dependent on
5   the energy of the cluster. However, second order effects are dependent on the velocity of the cluster which is dependent on both the energy of the cluster and it's mass (and hence the cluster size, N.) In order to maximize the utility of a gas cluster ion beam for surface processing, it
10 is useful to know and control both the energy of the cluster and the cluster size or cluster size distribution. In certain applications gas cluster ion beams are used for deposition or growth of surface films. When thus used it is important to know the mass flow to the workpiece. However,
15 unless the average size or size distribution (average mass or mass distribution) is also known, the total mass flow to the workpiece is not known. In the usual case, ionized clusters from a practical ionized cluster source, do not necessarily all carry the same number of electrical charges.
20 Under certain conditions it can be arranged that the cluster ions predominately carry a single electrical charge, and in such case it is accurately assumed that each charge corresponds to a single cluster, but unless the average size or size distribution (average mass or mass distribution) is
25 also known, the total mass flow to the workpiece is not known. It is possible, by controlling the source conditions, to influence the ratio of cluster ions to molecular ions and as well as to influence the cluster size distribution. However, unless a means is available to
30 measure and monitor the cluster size distribution and the ratio of cluster ions to molecular ions, optimal adjustment and control of the source conditions for influencing ionized cluster size is difficult. When the ionized clusters do not all predominately carry a single charge or a known number of
35 charges, knowledge of the ionized clusters' mass per charge can also be used as a useful parameter to control or adjust the beam's effectiveness for smoothing, etching, or other processing.

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For these and other reasons it is useful to have a means of measurement that can provide cluster size distribution information about a gas cluster ion beam or that can provide information about a gas cluster ion beam's

5   cluster-size-per-charge distribution or cluster-mass-per-charge distribution.

Because molecular ions, as well as cluster ions, are produced by presently available cluster ion beam sources, those molecular ions are accelerated and transported to the

10   workpiece being processed along with the cluster ions. Molecular ions, having high energy with low mass results in high velocities, which allow the light molecular ions to penetrate the surface and produce deep damage which is likely to be detrimental to the process.

15   It has become known in the ion cluster beam art that many GCIB processes benefit from incorporating means within GCIB processing equipment for eliminating molecular ions from the ion cluster beams. Electrostatic (see US patent 4,737,637, Knauer) and electromagnetic (see Japanese laid

20   open application JP 03-245523, cited as prior art in US patent 5,185,287, Aoyagi et al.) mass analyzers have been employed to remove light ions from the beam of heavier cluster ions. Electrostatic and electromagnetic mass analyzers have also been employed to select ion clusters

25   having a narrow range of ion masses from a beam containing a wider distribution of masses.

Presently practical GCIB sources produce a broad distribution of ion cluster sizes with limited cluster ion currents available. Therefore it is not practical to

30   perform GCICB processing by selecting a single cluster size or a narrow range of cluster sizes since the available fluence of such a beam is too low for productive processing. It is preferred to eliminate only the molecular ions and other lowest mass ions from the beam and use all remaining

35   heavier ions for processing. Practical experience has shown that it is often sufficient to provide filtering to eliminate molecular ions while depending on the typical cluster size distribution characteristics (few small size clusters are created by typical sources) to limit the small

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clusters (N = 2 to ~10) in the beam. Clusters of size N >
10 are adequately large to provide acceptable results in
most processes. Since the typical cluster distribution
contains clusters of up to N = several thousand and there
are few clusters of mass less than 100, it is not
significantly detrimental if clusters up to size 100 are
removed from the beam in the process of eliminating the
molecular ions. However, in order to adequately predict the
processing effectiveness of a gas cluster ion beam, it is
very desirable to know the distribution of masses or cluster
sizes in the beam and to know whether molecular ions and the
smallest size cluster ions are present or not.

It is therefore an object of this invention to provide
a way of measuring the distribution of cluster ion sizes in
a GCIB.

It is also an object of the invention to provide means
to determine the mass distribution and mass flow of cluster
ions in a GCIB.

It is also an object of the invention to determine the
presence or absence in a GCIB of undesirable molecular ions.

It is still another object of this invention to perform
cluster size and mass measurement concurrently with
workpiece processing

SUMMARY OF THE INVENTION

The objects set forth above as well as further and
other objects and advantages of the present invention are
achieved by the embodiments of the invention described
hereinbelow.

In the present invention it is preferably arranged that
the molecular and cluster ions produced in an ionization
system for gas clusters predominantly carry a single
electrical charge and such ions are accelerated through a
known acceleration potential. Based thereon, the ions, both
molecular ions and cluster ions, in a GCIB produced in the
apparatus of the invention have known and controllable
energies per ion, regardless of cluster size or whether the
ion is a cluster or a molecular ion. Since the ions are all

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generated from a pure gas, the molecular weight of each
molecule is known. Therefore, by measuring the times-of-
flight of the known ions of known energy over a known
distance, it is possible according to the invention to

5   calculate the mass and the cluster size of the ions.
Alternatively, when it is not practical or not desired to
arrange that all molecular and cluster ions produced in the
gas cluster ionization system predominately carry a single
electrical charge, in the present invention, by measuring

10   the times-of-flight of the ions it is possible to calculate
the mass per charge or size per charge of the ions.

By providing a selected scanning waveform and
introducing appropriate sensing apparatus in a conventional
GCIB processor, the invention makes an in situ capability

15   for measurement of the mass and cluster size distribution of
the ions in a GCIB. The invention separates the GCIB
pathway for processing from the GCIB pathway for mass and
size measurement, making it possible to perform the cluster
size and mass measurement concurrently with workpiece

20   processing.

For a better understanding of the present invention,
together with other and further objects thereof, reference
is made to the accompanying drawings and detailed
description and its scope will be pointed out in the

25   appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a graph showing typical ion cluster size

30   distribution for a GICB source;
Figure 2 is a schematic showing the basic elements of a
prior art GCIB processing system;
Figure 3 is a schematic showing a GCIB processing
system employing an embodiment of this invention;

35   Figure 4 is a schematic of a scan generator for y-scan
plates having beam-switching provision according to the
invention;
Figure 5 is a schematic of a time-of-flight analyzer
system of the invention;

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Figure 6 is a time-of-flight spectrum as can be shown on the time-of-flight analyzer display of the invention;

Figure 7 shows a schematic of a GCIB processing system employing an alternative embodiment of the invention; and

5   Figure 8 shows a positive scanning signal for an alternate embodiment of the GCIB processing system of this invention, having a deflected time-of-flight analysis beam path.

10   DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 shows the typical ion cluster size distribution produced by a commonly available GCIB source. The cluster formation process has been shown (in N. Kofuji,

15   et al., Development of gas cluster source and its characteristics, *Proc. 14th Symp. on Ion Sources and Ion-Assisted Technology*, Tokyo (1991) p. 15) to produce few small size clusters (values of N from 2 to about 10), but molecular ions (N = 1) are produced in abundance as are

20   larger clusters (N > a few tens, up to a few thousands.) It is known from the teachings of US patent 5,459,326, Yamada, that molecules in a cluster are not individually energetic enough (on the order of a few electron volts) to significantly penetrate a surface to cause the residual

25   surface damage typically associated with the other types of ion beam processing in which individual molecular ions may have energies on the order of thousands of electron volts. Nevertheless, according to Yamada and Matsuo, Cluster ion beam processing, *Matl. Science in Semiconductor Processing*

30   I, (1998) pp. 27-41, the clusters themselves can be made sufficiently energetic (some thousands of electron volts), to effectively etch, smooth or clean surfaces.

Figure 2 shows a typical configuration for a GCIB processor 100 of a form known in prior art, and which may be

35   described as follows: a vacuum vessel 102 is divided into three communicating chambers, a source chamber 104, an ionization/acceleration chamber 106, and a processing chamber 108. The three chambers are evacuated to suitable operating pressures by vacuum pumping systems 146a, 146b,

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and 146c, respectively. A condensable source gas 112 (for example argon or N_2) is admitted under pressure through gas feed tube 114 to stagnation chamber 116 and is ejected into the substantially lower pressure vacuum through a properly

5   shaped nozzle 110. A supersonic gas jet 118 results. Cooling, which results from the expansion in the jet, causes a portion of the gas jet 118 to condense into clusters, each consisting of from a few to several thousand weakly bound molecules. A gas skimmer aperture 120 separates the gas

10 products that have not been formed into a cluster jet from the cluster jet so as to minimize pressure in the downstream regions where such higher pressures would be detrimental (e.g., ionizer 122, high voltage electrodes 126, and process chamber 108).   Suitable condensable source gases 112

15 include, but are not limited to argon, nitrogen, carbon dioxide, oxygen.

        After the supersonic gas jet 118 containing gas clusters has been formed, the clusters are ionized in an ionizer 122. The ionizer 122 is typically an electron

20 impact ionizer that produces thermoelectrons from one or more incandescent filaments 124 and accelerates and directs the electrons causing them to collide with the gas clusters in the gas jet 118, where the jet passes through the ionizer 122. The electron impact ejects electrons from the

25 clusters, causing a portion the clusters to become positively ionized. A set of suitably biased high voltage electrodes 126 extracts the cluster ions from the ionizer, forming a beam, then accelerates them to a desired energy (typically from 1 keV to several tens of keV) and focuses

30 them to form a GCIB 128 having an initial trajectory 154. Filament power supply 136 provides voltage V_F to heat the ionizer filament 124. Anode power supply 134 provides voltage V_A to accelerate·thermoelectrons emitted from filament 124 to cause them to bombard the cluster containing

35 gas jet 118 to produce ions. Extraction power supply 138 provides voltage V_E to bias a high voltage electrode to extract ions from the ionizing region of ionizer 122 and to form a GCIB 128. Accelerator power supply 140 provides voltage V_{Acc} to bias a high voltage electrode with respect to

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the ionizer 122 so as to result in a total GCIB acceleration energy equal to V_{Acc}. One or more lens power supplies (142 and 144 shown for example) may be provided to bias high voltage electrodes with potentials (V_{L1} and V_{L2} for example)

5   to focus the GCIB 128.

A workpiece 152, which may be a semiconductor wafer or other workpiece to be processed by GCIB processing, is held on a workpiece holder 150, disposed in the path of the GCIB 128. Since most applications contemplate the processing of

10   large workpieces with spatially uniform results, a scanning system is desirable to uniformly scan the GCIB 128 across large areas to produce spatially homogeneous results. Two pairs of orthogonally oriented electrostatic scan plates 130 and 132 can be utilized to produce a raster or other

15   scanning pattern across the desired processing area. When beam scanning is performed, the GCIB 128 is converted into a scanned GCIB 148, which scans the entire surface of workpiece 152.

Figure 3 shows one possible embodiment of the invention

20   utilizing of a basic GCIB apparatus 200 having a modified configuration to implement the invention. In this embodiment, a fixed (DC) deflection voltage has been added to the beam scanning voltage waveforms at the Y-scan deflection plates 202 to impose a fixed offset angle 210

25   between the initial beam trajectory 154 and the central path 206 of the scanned GCIB 148, the offset being imposed in the region between the scan plates 202. At scan plates 202, in addition to being deflected in the amount of offset angle 210, the GCIB also is scanned through a scanning angle 226.

30   One half of the scan angle 226 is referred to as the scan half angle 208. Any uncharged molecules or clusters that may be present in the GCIB, are not responsive to the electrostatic field between scan plates 202, and continue in a straight line along path 204, which extends to a region

35   now separated from the workpiece 152 processing region. A Faraday enclosure 222 having a suppressor ring electrode 216 and a grounded ring electrode 218 at the beam entrance opening of the Faraday enclosure 222 is disposed in the path of the straight line path 204, which is an extension of the

initial beam trajectory 154. The suppressor ring electrode
216 is negatively biased with respect to the Faraday
enclosure 222 by a bias power supply, E_s, so as to permit
entrance of any energetic ions or uncharged particles
5   traveling along path 204 with minimal influence, but yet
also prevent the exit of low energy electrons, thus
retaining all secondary electrons that may be produced in
the Faraday enclosure 222. Thus, if any uncharged molecules
or clusters are stopped in the Faraday enclosure 222, they
10 have no electrical effect, but any ions that are stopped in
the Faraday enclosure have their charged conducted by lead
220 to a time-of-flight analysis system 400. Workpiece 152
is held and positioned in the path of the scanned GCIB 148
and away from the Faraday enclosure 222 and the undeflected
15 path 204 by workpiece holder 150.

     Still referring to Figure 3, the beam entrance to scan
plates 202 is separated from the entrance to the Faraday
enclosure 222 by a drift distance, D, which may be any
convenient distance, preferably many times greater than the
20 length of scan plates 202 and also preferably greater than
30 cm. A scan generator 300 provides y-axis scanning
voltages and deflection voltages to scan plates 202 through
leads 212 and 214. Scan generator 300 also provides
synchronization pulses to the time-of-flight analysis system
25 400 through lead 224.

     Figure 3 further shows, for purposes of example, but
not for limitation, a fixed angular deflection of the
central path 206 from the scanned GCIB 148 of approximately
15 degrees from the initial beam trajectory 154 and its
30 extended undeflected path 204, however, it is apparent that
any deflection slightly larger than the scan half-angle 208
is potentially adequate to separate the scanned GCIB 148
from the undeflected path 204.

     Figure 4 shows details of scan generator 300 and of the
35 signals it produces. The scan generator 300 produces
scanning, deflection, and beam switching signals for y-scan
plates 202 and produces synchronization signals for use by
the time-of-flight analysis system 400. A digital sequence
generator 302 produces sequences of binary number and

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control signals that flow to a digital-to-analog converter
(DAC) 306 through signal bus 304. The digital sequence
generator 302 may consist of a microprocessor, micro-
controller, small computer, or other digital logic system
5   capable of generating the necessary digital number sequences
and control signals for the DAC 306. It is easily
appreciated that the digital sequence generator and its
control may be implemented by any of a variety of techniques
that are well known to those skilled in the art of digital
10 and computer logic. The digital sequence generator may
furthermore communicate by way of a communication bus 324
with an optional remote digital system controller 326.
Although such a digital system controller may be part of an
overall automated control system for a GCIB processing
15 apparatus and may be desirable from a point of convenience
and efficiency in integrating and coordinating the functions
of a GCIB processor, it is not a necessary part of the
invention. Accordingly, the digital system controller 326
and the communication bus 324 are shown for purposes of
20 example and not for limitation.

        Still referring to Figure 4, the binary number
sequences and control signals provided by the digital
sequence generator 302 enable the DAC 306 to produce a y-
scanning signal that is amplified by inverting amplifier 308
25 and non-inverting amplifier 310 and by high-voltage
amplifiers 312 and 314 to produce high level scanning
signals 316 and 318 which are connected to the y-scan plates
202 by leads 214 and 212 respectively. During normal
processing operations, the scan generator 300 produces a
30 periodic saw-tooth waveform for each plate, having a period,
t_{scn}, (which could, for example, but without limitation, be
on the order of 1 to 100 milliseconds) and an amplitude
suitable to produce the desired scan angle 226. Consider
the scanning signal 318: The periodic saw-tooth waveform is
35 superimposed on a DC deflection voltage, V_D, which is chosen
to impose a fixed offset angle 210 between the initial beam
trajectory 154 and the central path 206 of the scanned GCIB
148 as the beam travels through the region between the scan
plates 202.

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From time to time as required, either at least once
before the start of GCIB processing, or preferably,
repeatedly during GCIB processing, the digital sequence
generator intersperses a beam switching pulse among the
5   periodic saw-tooth scan waves. The timing of the waveform
segments shown in the plots for signals 316 and 318 is
chosen to include one such beam switching pulse. In the
illustrated scanning signals, 316 and 318, the onset of the
beam switching pulse is labeled t_0 and the duration of the
10   beam switching pulse is labeled t_{pw} During the beam switching
pulse duration, the y-scanning signal voltage is zero, and
for that reason, the GCIB is not deflected by offset angle
210 and is not scanned through scan angle 226, but, rather,
travels undeflected through the region of y-scan plates 202
15   along the straight line path 204, which is an extension of
the initial beam trajectory 154. Accordingly said
undeflected GCIB flies in a straight line to the Faraday
enclosure 222, where it is stopped and the charge in the
ions is converted into a detected current which flows into
20   time-of-flight analyzer 400 through lead 220. At time t_0 +
t_{pw}, the beam switching pulse ends, periodic saw-tooth
scanning begins, the beam switches back to the offset path
which is directed at the workpiece 152 and GCIB processing
resumes. Note that scanning signal 316 is the negative of
25   scanning signal 318. A sample of the scanning signal 308 is
conducted to pulse shaping circuit 320. Pulse shaping
circuit processes the scanning signal to extract and provide
a synchronization pulse signal 322 which has a leading edge
occurring at time t_0, synchronous with the onset of the beam
30   switching pulse to the scan plates 202.   The
synchronization pulse signal 322 is shown, for example, but
not for limitation, to have a pulse duration equal to t_{spw},
which may be equal to or different from t_{pw}. Synchronization
pulse signal 322 is conducted by lead 224 to the time-of-
35   flight analyzer 400. During the beam switching pulse
duration, t_{pw}, molecular ions and cluster ions entering the
entrance receive no deflection and so form a pulse of ions
directed toward the Faraday enclosure 222. The undeflected
ion pulse may contain molecular ions and cluster ions of

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various masses and correspondingly various velocities. As
the ions fly toward the Faraday enclosure 222, their
velocity differences cause them to become dispersed along
the path 204 to the Faraday enclosure 222 and the ion pulse
5   becomes extended. Consequently, the arrival times of the
ions at the entrance to the Faraday enclosure 222 are
delayed by different amounts related to their velocities.

Figure 5 shows one embodiment of a time-of-flight
analyzer 400 to be used in the invention. The arrival of
10   the electrically charged ions in the Faraday enclosure 222
results in a corresponding current waveform induced in lead
220 to the time-of-flight analyzer 400. A short delay time,
t_p, after t_o, the lightest, fastest ions arrive at the
Faraday enclosure and are converted to an electrical current
15   signal. According to their dispersion, the heavier, slower
ions arrive later, with the heaviest, slowest ions arriving
at the delayed time, t_s. The total current signal 402
collected by the Faraday enclosure as a result of the flight
of a single dispersed ion pulse resulting from a single beam
20   switching pulse may appear, for example, as shown the time
amplitude plot 402 (current signal) in Figure 5. In the
example chosen for illustration of the principle, there is a
current peak at time t_p corresponding to the prompt arrival
of the molecular ions and a broader peak occurring between
25   t_p and t_s corresponding to the arrival of the slower cluster
ions. Current-to-voltage converter 404 receives the current
signal 402 and produces a voltage signal subsequently
amplified by amplifier 406. The time-of-flight analyzer 400
also receives a synchronization pulse signal 322 conducted
30   by lead 224 from scan generator 300. A digital storage
oscilloscope 408, having a trigger signal input 414, at
least one vertical signal input 412, internal time base
generator for generating a display sweep signal, and a
visual display 410 receives the synchronization pulse signal
35   322 and the amplified voltage signal derived from the
current signal 402. Oscilloscope digitizes, stores, and
displays the signal presented at vertical input 412, which
is a time-of-flight spectrum for the ions in the single beam
pulse resulting from one beam switching pulse.

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Oscilloscope 410 may also have data communications
capabilities and remote readout capabilities and may
communicate by way of a communication bus 416 with an
optional digital system controller 326. Although such a
5   digital system controller may be part of an overall
automated control system for a GCIB processing apparatus and
may be desirable from a point of convenience and efficiency
in integrating and coordinating the functions of a GCIB
processor, it is not a necessary part of the invention.
10   Accordingly, the digital system controller 326 and the
communication bus 324 are shown for purposes of example and
not for limitation. When an optional digital system
controller is employed, is often has sufficient
computational power to permit more sophisticated analysis
15   and processing of the information in the time-of-flight
signal.

The time of flight resolution of the current signal 402
is dependent on the flight distance D and the duration of
the beam switching pulse t_{pw} for a given beam energy. It is
20 · preferable that the duration of the beam switching pulse be
shorter by at least a factor of 10 than the flight time of
the ions over the distance D. With a short t_{pw}, the current
signal 402 approaches the true time-of-flight spectrum.
With longer values of t_{pw}, the beam switching pulse duration
25   t_{pw} becomes mathematically convolved with the time-of-flight
spectrum. In such a case, it must be deconvolved in order
to provide a spectrum with acceptable time-of-flight
resolution. It is preferable that the duration of the beam
switching pulse width t_{pw} be less than one tenth of the time-
30   of-flight of the lightest ion for which good resolution is
desired. When t_{pw} is short compared to the flight time of
the molecular ions, the oscilloscope display 410 will have
good resolution for even the molecular ions, and a time-of-
flight spectrum 550 such as shown in Figure 6 is produced on
35   the display 410.

When t_{pw} is short compared to the time-of-flight, the
ion or cluster ion mass is related to the time-of-flight as
follows:

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$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2}$$ (Eqn. 1)

where m_i = mass of ion (or cluster ion)

E = GCIB energy

v = velocity of ion (or cluster ion)

D = ion (or cluster ion) flight distance

$t_d = t - t_0$ = ion (or cluster ion) time of flight

V_{ACC} = total beam acceleration potential

q = cluster charge state

e = unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m}$$ (Eqn. 2)

where N = cluster size

m_i = mass of ion (or cluster ion)

m_m = mass of a molecule of the gas forming

clusters

Using Eqn. 2 and the value of m_i from Eqn. 1 it is possible to determine the relationship between t_d, the time of flight of a cluster ion and its cluster size, thus making it possible to label the x-axis of the display 550 shown on the display 410 in units of cluster size, N, as well as in time-of-flight time units.

When the ionized clusters all bear a single charge equal in magnitude to the unit charge (electronic charge), e, then q=1 and Eqn. 1 and Eqn. 2 calculate the cluster size N. However, in general the ionized clusters may have a distribution in both size N and in charge state q, q being the number of electronic charges held by the ion. At the present, there is no easy separation of these distributions. Consequently in this case the time-of-flight measurement is used to measure the distribution of N':

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$$N' = \frac{N}{q} \qquad\qquad (\text{Eqn. 3})$$

where q = cluster charge state.

While this generalization somewhat reduces the utility
5   of the measurement, the time-of-flight derived N'
distribution is very useful in determining consistency of
operation in commercial production equipment and for
facilitating the set-up of equipment operating parameters to
achieve consistent processing. Moreover, it is often
10   possible to infer the size distribution separately by
operating the cluster ionizer at low levels so that it is
unlikely that the clusters acquire more than a single charge
each -- in such case the approximation that q = e (ions are
singly ionized) is justified.
15   The GCIB processing system 200 shown in Figure 3
incorporates an embodiment of the invention which although
operable, may be viewed as having a minor drawback. As
drawn in Figure 3, straight-line path 204 passes very near
to the x-scan plates 132. As a result the pulses of GCIB
20   that are undeflected by scan plates 202 and therefore travel
along straight line path 204 may be influenced by any x-
scanning electrical field between the x-scan plates 132,
causing the GCIB pulse which was not deflected at plates 202
to receive a small amount of scanning at scan plates 132.
25   This condition may be tolerated by choosing the shape
Faraday enclosure 222 to have a shape that is elongated in
the x-scan direction so as to collect all of the GCIB pulse
even though it is somewhat extended in the x-scanning axis
direction. Alternatively, the condition of concern, namely
30   that the straight line path 204 passes near to the x-scan
plates 132, can be avoided by increasing the fixed offset
angle 210, or by increasing the spacing between scan plates
202 and scan plates 132 by moving scan plates 132 further
downstream the central beam path 206. Although these are
35   various means to deal with the proximity of the straight-
line path to the x-scan plates 132, Figure 7 shows an

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alternate embodiment of the invention, which avoids the problem in a different way.

The GCIB processing system 250 shown in Figure 7 is similar to the GCIB processing system 200 shown in Figure 3 except that rather than disposing the Faraday enclosure 222 along the straight line path 204, which is an extension of the initial beam trajectory 154, it is instead disposed along a deflected path 252 which is deflected away from the central path 206 by a separation angle 254 that is greater than the offset angle 210 by an amount that separates the deflected path 252 from the x-scan plates 132 sufficiently for the beam pulse traveling along the deflected path 252 to avoid any scanning effects from x-scan plates 132. Such deflection can be achieved by utilizing a scanning signal 500 as shown in Figure 8.

In Figure 8, note that the scanning signal 500 is identical to the scanning signal 318 shown for the first embodiment except that the beam switching pulse switches to a value of $-V_{D2}$ rather than zero. The negative value of $-V_{D2}$ causes the switched beam pulse to travel along deflected path 252 rather than along straight-line path 204. Scanning signal 500 represents the positive scanning signal applied to lead 212. Of course, there is a corresponding signal that is the negative of the scanning signal 500, which is generated and placed on lead 214. Scan generator 300 can generate signal 500 and its negative provided that the DAC 306, amplifiers 308, 310, 312, and 314 all have bipolar output capabilities and provided that the digital sequence generator 302 generates the corresponding digital sequences having negative values for the beam switching pulse period.

48 Once gas cluster ion beam cluster mass and/or cluster size and/or cluster size per charge and/or cluster mass per charge is determined by the present invention as described in the various embodiments set forth above, appropriate adjustments (for example adjusting source gas flow or adjusting ionizer filament voltage VF or anode voltage VA) can be made to the GCIB apparatus via conventional manual operator controls or via conventional

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feedback circuitry connected to conventional automation controls in order to maintain preferred gas cluster ion beam cluster mass and/or cluster size and/or cluster size or mass per charge during workpiece processing to assure proper quality or rate of processing, and thereby improving the processing of the workpiece. Alternatively, during workpiece processing, gas cluster ion beam cluster characteristics may be determined to assure proper continued workpiece processing. Should cluster characteristics drift out of desired specifications, conventional control and alarm circuitry can suspend processing and signal for operator attention to restore proper processing conditions, and thereby improve the processing of the workpiece.

Although the invention has been described with respect to various embodiments, it should be realized this invention is also capable of a wide variety of further and other embodiments within the spirit and scope of the appended claims.

What is claimed is:

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CLAIMS

1. An apparatus for gas cluster ion beam (GCIB) mass or
   cluster size diagnostics for improving GCIB workpiece
5 processing, comprising:
       a vacuum vessel;
       a gas cluster ion beam source within the vacuum vessel
   for producing a gas cluster ion beam;
       an accelerator for accelerating the gas cluster ion
10 beam along a first trajectory;
       a beam deflector for controllably deflecting the gas
   cluster ion beam along a second trajectory, said second
   trajectory diverging from said first trajectory by a
   predetermined offset angle;
15   beam detection means disposed along said first
   trajectory at a predetermined distance, D, from said beam
   deflector;
       workpiece holding means disposed along the second
   trajectory for holding a workpiece for gas cluster   ion
20 beam processing;
       control means for providing deflection signals to said
   beam deflector for controllably deflecting the gas
   cluster ion beam between said first trajectory and said
   second trajectory;
25   time-of-flight measurement means for measuring the
   times-of-flight of components of the gas cluster ion beam
   over said distance, D; and
       a time-of-flight analyzer to analyze said times of
   flight of components of the gas cluster ion beam in order
30 to provide output information relative to GCIB mass or
   cluster size;
       wherein said output information is used in the gas
   cluster ion beam processing of the workpiece.

35 2. The apparatus of claim 1, further comprising display
   means for displaying the times-of-flight of components of
   the gas cluster ion beam.

19

3. The apparatus of claim 1, further comprising display
   means for displaying an estimate of the size or mass
   distribution of cluster components of the gas cluster ion
   beam based upon said output information.

5

4. The apparatus of claim 1, further comprising system
   control means operably connected to said time-of-flight
   analyzer for receiving output information and for
   controlling the gas cluster ion beam processing of the
10   workpiece.

5. The apparatus of claim 1, wherein the beam detection
   means comprises a faraday enclosure for collecting beam
   current signals.

15

6. The apparatus of claim 1, wherein the deflection signals
   comprise a beam switching signal that switches a beam
   pulse along said first trajectory in order to measure the
   times-of-flight of components of the gas cluster ion beam
20   over said distance, D.

7. The apparatus of claim 6, wherein the accelerator
accelerates the gas cluster ion beam to an energy in the
range of from about 1 keV to about 50 keV.

25

8. The apparatus of claim 7, wherein the time duration of
the beam switching signal is less than 10% of the time-of-
flight for ions of size N being 500 or greater.

30   9. The apparatus of claim 1, wherein the output information
relative to GCIB mass or cluster size is ascertained by the
following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

   where m_i = mass of ion (or cluster ion)

35   E = GCIB energy

          v = velocity of ion (or cluster ion)

20

$D =$ ion (or cluster ion) flight distance

$t_d = t - t_0 =$ ion (or cluster ion) time of flight

$V_{ACC} =$ total beam acceleration potential

$q = 1 =$ cluster charge state

$e =$ unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad\qquad \text{(Eqn. 2)}$$

where $N =$ cluster size

$m_i =$ mass of ion (or cluster ion)

$m_m =$ mass of a molecule of the gas forming

clusters.

10. The apparatus of claim 1, wherein the output information relative to GCIB mass or cluster size is ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where $m_i =$ mass of ion (or cluster ion)

$E =$ GCIB energy

$v =$ velocity of ion (or cluster ion)

$D =$ ion (or cluster ion) flight distance

$t_d = t - t_0 =$ ion (or cluster ion) time of flight

$V_{ACC} =$ total beam acceleration potential

$q =$ cluster charge state

$e =$ unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad\qquad \text{(Eqn. 2)}$$

where $N =$ cluster size

$m_i =$ mass of ion (or cluster ion)

$m_m =$ mass of a molecule of the gas forming

clusters

and

$$N' = \frac{N}{q} \qquad\qquad (\text{Eqn. 3})$$

5   where q = cluster charge state.

11.   An apparatus for gas cluster ion beam (GCIB) mass or
cluster size diagnostics for improving GCIB workpiece
processing, comprising:

10   a vacuum vessel;
           a gas cluster ion beam source within the vacuum vessel
       for producing a gas cluster ion beam;
           an accelerator for accelerating said gas cluster ion
       beam along a first trajectory;

15   a beam deflector for controllably deflecting the gas
       cluster ion beam along a second trajectory said second
       trajectory diverging from said first trajectory by a
       predetermined first offset angle, and for controllably
       deflecting the gas cluster ion beam along a third

20   trajectory, said third trajectory diverging from said
       second trajectory by a predetermined second offset angle
       greater than said predetermined first offset angle;
           beam detection means disposed along the third
       trajectory at a predetermined distance, D, from the beam

25   deflector;
           workpiece holding means disposed along said second
       trajectory for holding a workpiece for gas cluster ion
       beam processing;
           control means for providing deflection signals for

30   controllably deflecting the gas cluster ion beam between
       said second trajectory and said third trajectory;
           time-of-flight measurement means for measuring the
       times-of-flight of components of the gas cluster ion beam
       over said distance, D; and

35   a time-of-flight analyzer to analyze said times of
       flight of components of the gas cluster ion beam in order

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to provide output information relative to GCIB mass or
cluster size;

wherein said output information is used in the gas
cluster ion beam processing of the workpiece.

12. The apparatus of claim 11, further comprising display
means for displaying the times-of-flight of components of
the gas cluster ion beam.

13. The apparatus of claim 11, further comprising display
means for displaying an estimate of the size or mass
distribution of cluster components of the gas cluster ion
beam based upon said output information.

14. The apparatus of claim 11, further comprising system
control means operably connected to said time-of-flight
analyzer for receiving output information and for
controlling the gas cluster ion beam processing of the
workpiece.

15. The apparatus of claim 11, wherein the beam detection
means comprises a faraday enclosure for collecting beam
current signals.

16. The apparatus of claim 11, wherein the deflection
signals comprise a beam switching signal that switches a
beam pulse along said third trajectory in order to measure
the times-of-flight of components of the gas cluster ion
beam over said distance, D.

17. The apparatus of claim 16, wherein the accelerator
accelerates the gas cluster ion beam to an energy in the
range of from about 1 keV to about 50 keV.

18. The apparatus of claim 17, wherein the time duration of
the beam switching signal is less than 10% of the time-of-
flight for ions of size N being 500 or greater.

23

19. The apparatus of claim 11, wherein the output information relative to GCIB mass or cluster size is ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

5   where m_i = mass of ion (or cluster ion)

            E = GCIB energy

            v = velocity of ion (or cluster ion)

            D = ion (or cluster ion) flight distance

            $t_d = t - t_0$ = ion(or cluster ion) time of flight

10   V_{ACC} = total beam acceleration potential

            q = 1 = cluster charge state

            e = unit charge (electronic charge)

and

15      $$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

        where N = cluster size

            m_i = mass of ion (or cluster ion)

            m_m = mass of a molecule of the gas forming

        clusters.

20

20. The apparatus of claim 11, wherein the output information relative to GCIB mass or cluster size is ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

25   where m_i = mass of ion (or cluster ion)

            E = GCIB energy

            v = velocity of ion (or cluster ion)

            D = ion (or cluster ion) flight distance

            $t_d = t - t_0$ = ion(or cluster ion) time of flight

30   V_{ACC} = total beam acceleration potential

24

$q =$ cluster charge state

$e =$ unit charge (electronic charge)

and

5       $$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where $N =$ cluster size

$m_i =$ mass of ion (or cluster ion)

$m_m =$ mass of a molecule of the gas forming

clusters

10

and

$$N' = \frac{N}{q} \qquad \text{(Eqn. 3)}$$

where $q =$ cluster charge state.

15

21.   An apparatus for gas cluster ion beam (GCIB) mass or
cluster size diagnostics for improving GCIB workpiece
processing, comprising:
        a vacuum vessel;
20   a gas cluster ion beam source within the vacuum vessel
    for producing a gas cluster ion beam;
        an accelerator for accelerating the gas cluster ion
    beam along a first trajectory;
        a beam deflector for controllably deflecting the gas
25   cluster ion beam along a second trajectory, said second
    trajectory diverging from said first trajectory by a
    predetermined offset angle;
        beam detection means disposed along said first
    trajectory at a predetermined distance, D, from said beam
30   deflector;
        control means for providing deflection signals to said
    beam deflector for controllably deflecting the gas
    cluster ion beam between said first trajectory and said
    second trajectory;

time-of-flight measurement means for measuring the
times-of-flight of components of the gas cluster ion beam
over said distance, D; and

a time-of-flight analyzer to analyze said times of
5   flight of components of the gas cluster ion beam in order
to provide output information relative to GCIB mass or
cluster size.

22. The apparatus of claim 21, wherein the output
10   information relative to GCIB mass or cluster size is
ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where m_i = mass of ion (or cluster ion)

E = GCIB energy

15   v = velocity of ion (or cluster ion)

D = ion (or cluster ion) flight distance

$t_d = t - t_0$ = ion(or cluster ion) time of flight

V_{ACC} = total beam acceleration potential

q = 1 = cluster charge state

20   e = unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where N = cluster size

25   m_i = mass of ion (or cluster ion)

m_m = mass of a molecule of the gas forming

clusters.

23. The apparatus of claim 12, wherein the output
30   information relative to GCIB mass or cluster size is
ascertained by the following formula:

26

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where m_i = mass of ion (or cluster ion)

E = GCIB energy

v = velocity of ion (or cluster ion)

D = ion (or cluster ion) flight distance

$t_d = t - t_0$ = ion(or cluster ion) time of flight

V_{ACC} = total beam acceleration potential

q = cluster charge state

e = unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where N = cluster size

m_i = mass of ion (or cluster ion)

m_m = mass of a molecule of the gas forming

clusters

and

$$N' = \frac{N}{q} \qquad \text{(Eqn. 3)}$$

where q = cluster charge state.

24. An apparatus for gas cluster ion beam (GCIB) mass or cluster size diagnostics for improving GCIB workpiece processing, comprising:

a vacuum vessel;

a gas cluster ion beam source within the vacuum vessel for producing a gas cluster ion beam;

an accelerator for accelerating said gas cluster ion beam along a first trajectory;

a beam deflector for controllably deflecting the gas cluster ion beam along a second trajectory said second

trajectory diverging from said first trajectory by a
predetermined first offset angle, and for controllably
deflecting the gas cluster ion beam along a third
.trajectory, said third trajectory diverging·from said
second trajectory by a predetermined second offset angle
greater than said predetermined first offset angle;

   beam detection means disposed along the third
trajectory at a predetermined distance, D, from the beam
deflector;

   control means for providing deflection signals for
controllably deflecting the gas cluster ion beam between
said second trajectory and said third trajectory;

   time-of-flight measurement means for measuring the
times-of-flight of components of the gas cluster ion beam
over said distance, D; and

   a time-of-flight analyzer to analyze said times of
flight of components of the gas cluster ion beam in order
to provide output information relative to GCIB mass or
cluster size;

   wherein said output information is used in the gas
cluster ion beam processing of the workpiece.

25. The apparatus of claim 24, wherein the output
information relative to GCIB mass or cluster size is
ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where m_i = mass of ion (or cluster ion)

   E = GCIB energy

   v = velocity of ion (or cluster ion)

   D = ion (or cluster ion) flight distance

   $t_d = t - t_0$ = ion(or cluster ion) time of flight

   V_{ACC} = total beam acceleration potential

   q = 1 = cluster charge state

   e = unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where N = cluster size

m_i = mass of ion (or cluster ion)

m_m = mass of a molecule of the gas forming

clusters.

26. The apparatus of claim 24, wherein the output
information relative to GCIB mass or cluster size is
ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where m_i = mass of ion (or cluster ion)

E = GCIB energy

v = velocity of ion (or cluster ion)

D = ion (or cluster ion) flight distance

$t_d = t - t_0$ = ion(or cluster ion) time of flight

V_{ACC} = total beam acceleration potential

q = cluster charge state

e = unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where N = cluster size

m_i = mass of ion (or cluster ion)

m_m = mass of a molecule of the gas forming

clusters

and

$$N' = \frac{N}{q} \qquad \text{(Eqn. 3)}$$

29

where q = cluster charge state.

27. A method for gas cluster ion beam (GCIB) mass or cluster size diagnostics for improving GCIB workpiece processing, comprising:

providing a gas cluster ion beam source;

producing a gas cluster ion beam with said ion beam source;

accelerating the gas cluster ion beam along a first trajectory;

controllably deflecting the gas cluster ion beam between said first trajectory and said second trajectory, said second trajectory being offset from said first trajectory by a predetermined offset angle;

defining a predetermined distance, D, along said first trajectory;

detecting the gas cluster ion beam along said first trajectory at said predetermined distance, D;

measuring the times-of-flight of components of the gas cluster ion beam over said distance, D; and

analyzing said times of flight of components of the gas cluster ion beam in order to provide output information relative to GCIB mass or cluster size.

28. The method of claim 27, wherein the output information relative to GCIB mass or cluster size is ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where m_i = mass of ion (or cluster ion)

E = GCIB energy

v = velocity of ion (or cluster ion)

D = ion (or cluster ion) flight distance

$t_d = t - t_0$ = ion (or cluster ion) time of flight

V_{ACC} = total beam acceleration potential

$q = 1$ = cluster charge state

30

$e =$ unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where $N =$ cluster size

   $m_i =$ mass of ion (or cluster ion)

   $m_m =$ mass of a molecule of the gas forming

clusters.

29. The apparatus of claim 27, wherein the output
information relative to GCIB mass or cluster size is
ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where $m_i =$ mass of ion (or cluster ion)

   $E =$ GCIB energy

   $v =$ velocity of ion (or cluster ion)

   $D =$ ion (or cluster ion) flight distance

   $t_d = t - t_0 =$ ion(or cluster ion) time of flight

   $V_{ACC} =$ total beam acceleration potential

   $q =$ cluster charge state

   $e =$ unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where $N =$ cluster size

   $m_i =$ mass of ion (or cluster ion)

   $m_m =$ mass of a molecule of the gas forming

clusters

and

$$N' = \frac{N}{q} \qquad \text{(Eqn. 3)}$$

31

where q = cluster charge state.

30. The method of claim 27, further comprising:

    situating a workpiece in a predetermined location

5   within said second trajectory; and

    using said output information relative to GCIB mass or

cluster size to improve processing the workpiece

31. A method for gas cluster ion beam (GCIB) mass or

10 cluster size diagnostics for improving GCIB workpiece

    processing, comprising:

        providing a gas cluster ion beam source;

        producing a gas cluster ion beam with said ion beam

    source;

15   accelerating the gas cluster ion beam along a first

    trajectory;

        controllably deflecting the gas cluster ion beam

    between said second trajectory and a third trajectory,

    said second trajectory being offset from said first

20 trajectory by a predetermined first offset angle and said

    third trajectory being offset from said second trajectory

    by a second predetermined offset angle, said second

    offset angle being greater than said first offset angle;

        defining a predetermined distance, D, along said third

25 trajectory;

        detecting the gas cluster ion beam along said third

    trajectory at said predetermined distance, D;

        measuring the times-of-flight of components of the gas

    cluster ion beam over said distance, D; and

30   analyzing said times of flight of components of the gas

    cluster ion beam in order to provide output information

    relative to GCIB mass or cluster size.

32. The method of claim 31, wherein the output information

35 relative to GCIB mass or cluster size is ascertained by the

    following formula:

32

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where $m_i = $ ·mass of ion (or cluster ion)

$E =$ GCIB energy

$v =$ velocity of ion (or cluster ion)

$D =$ ion (or cluster ion) flight distance

$t_d = t - t_0 =$ ion(or cluster ion) time of flight

$V_{ACC} =$ total beam acceleration potential

$q = 1 =$ cluster charge state

$e =$ unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad \text{(Eqn. 2)}$$

where $N =$ cluster size

$m_i =$ mass of ion (or cluster ion)

$m_m =$ mass of a molecule of the gas forming

clusters.

33. The apparatus of claim 31, wherein the output information relative to GCIB mass or cluster size is ascertained by the following formula:

$$m_i = \frac{2E}{v^2} = \frac{2E}{\left(\dfrac{D}{t_d}\right)^2} = \frac{2E(t_d)^2}{D^2} = \frac{2qeV_{ACC}(t_d)^2}{D^2} \qquad \text{(Eqn. 1)}$$

where $m_i =$ mass of ion (or cluster ion)

$E =$ GCIB energy

$v =$ velocity of ion (or cluster ion)

$D =$ ion (or cluster ion) flight distance

$t_d = t - t_0 =$ ion(or cluster ion) time of flight

$V_{ACC} =$ total beam acceleration potential

$q =$ cluster charge state

$e =$ unit charge (electronic charge)

and

$$N = \frac{m_i}{m_m} \qquad\qquad \text{(Eqn. 2)}$$

where $N =$ cluster size

$m_i =$ mass of ion (or cluster ion)

$m_m =$ mass of a molecule of the gas forming

clusters

and

$$N' = \frac{N}{q} \qquad\qquad \text{(Eqn. 3)}$$

where $q =$ cluster charge state.

34. The method of claim 31, further comprising:
      situating a workpiece in a predetermined location
within said second trajectory; and
      using said output information relative to GCIB mass or
cluster size to improve processing the workpiece.

**Typical cluster ion size distribution**
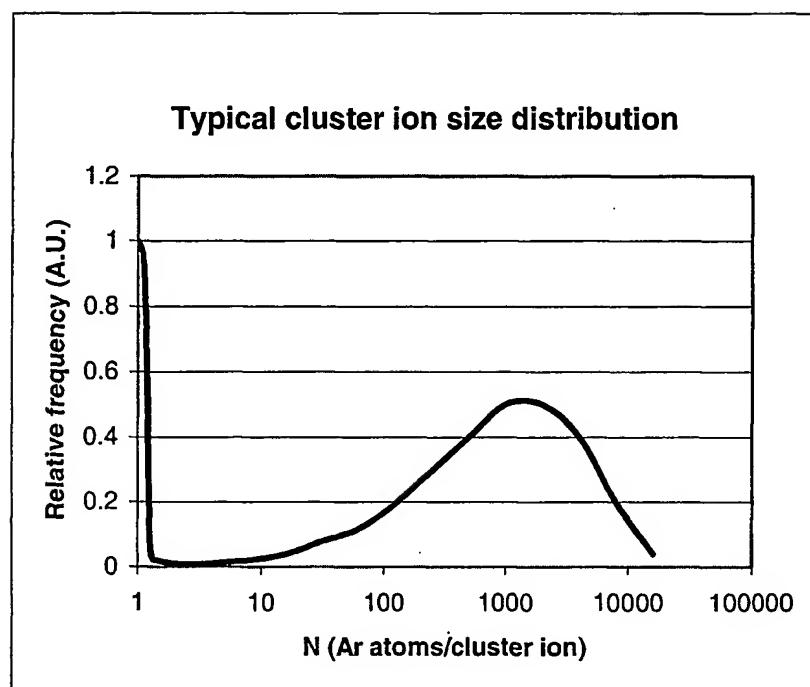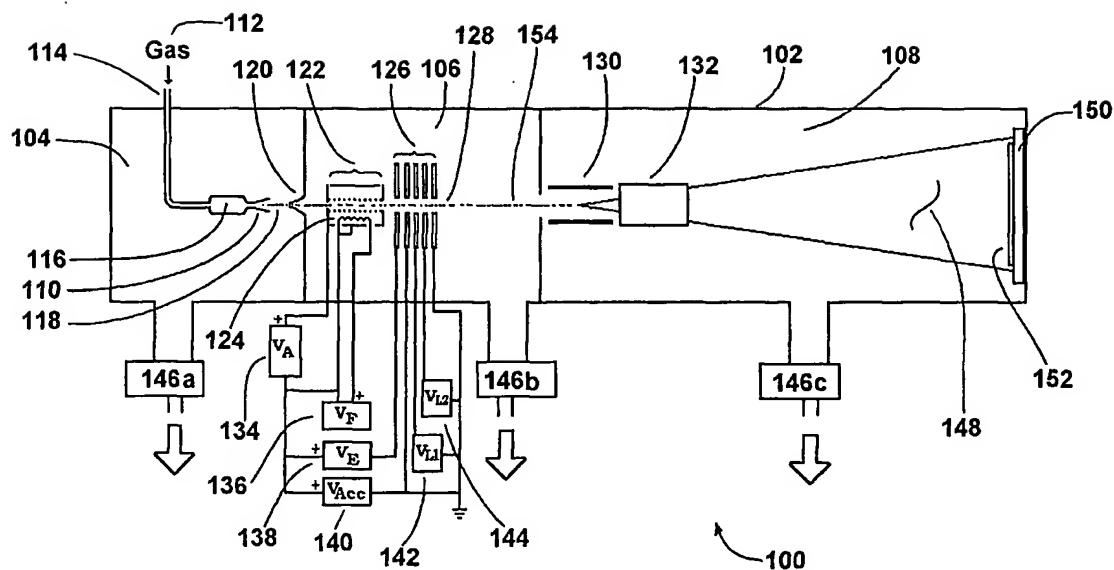
Figure 1, Prior Art

Figure 2, Prior Art
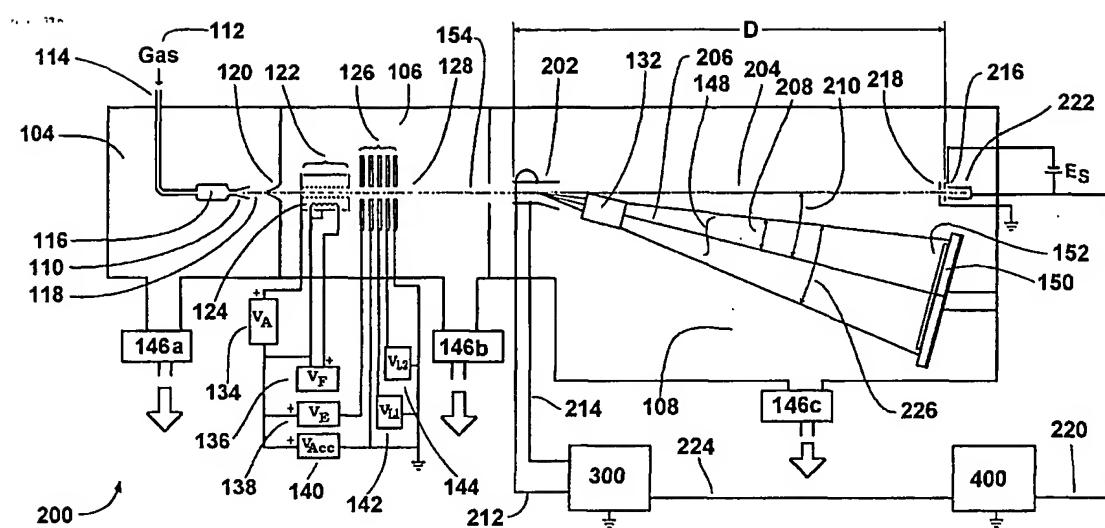
Figure 3
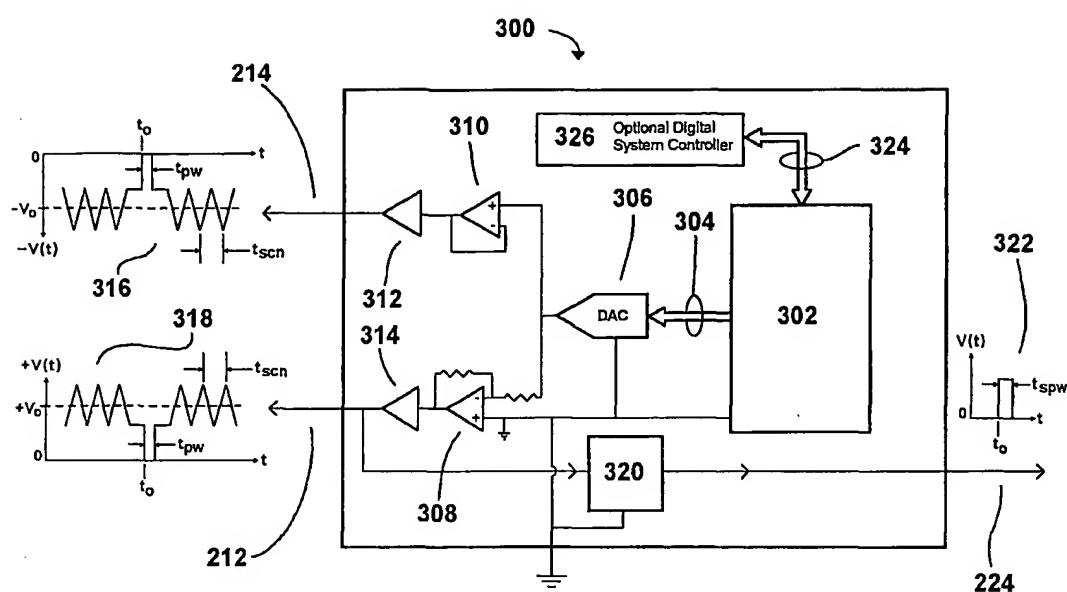
Figure 4
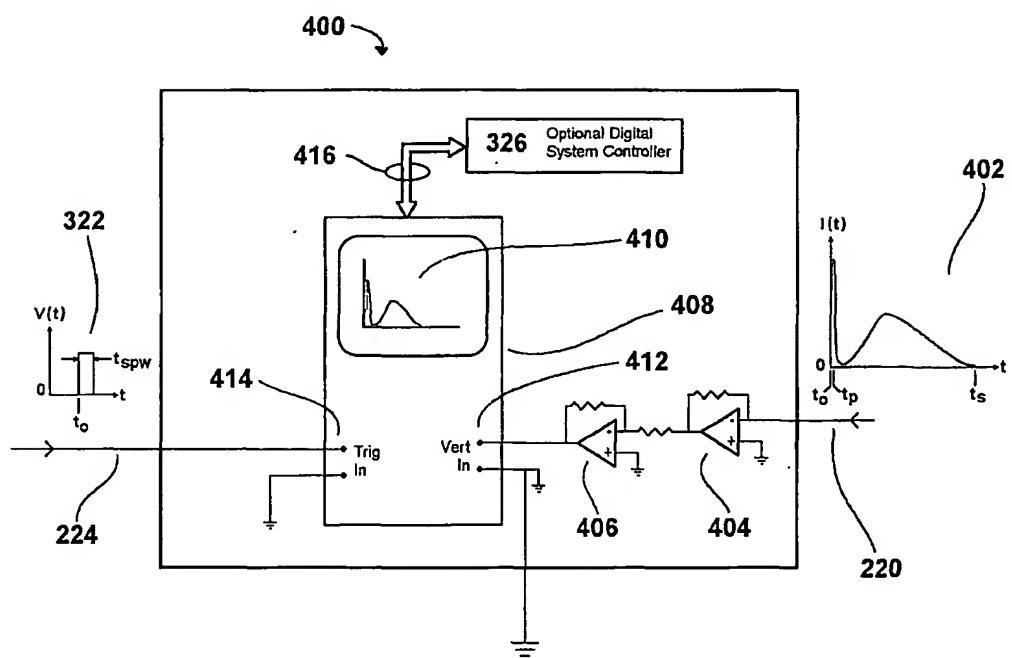
Figure 5
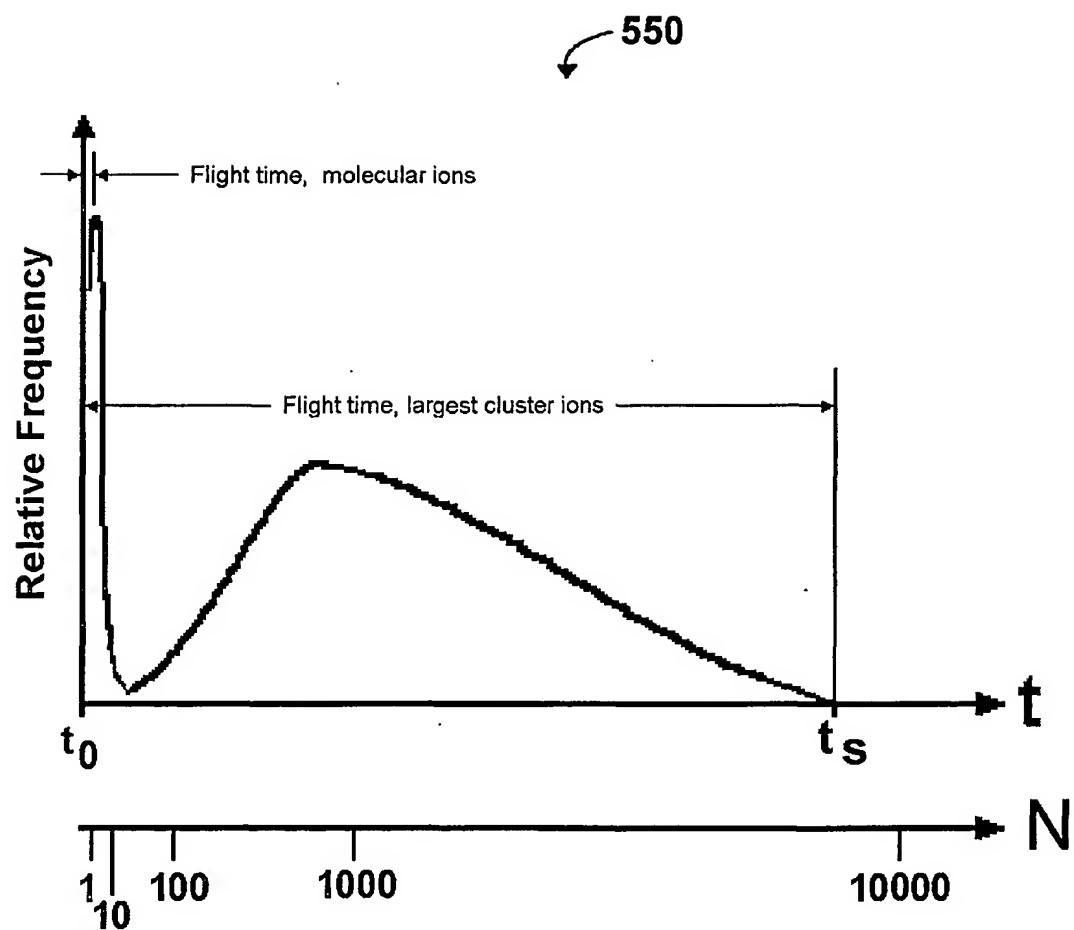
Figure 6
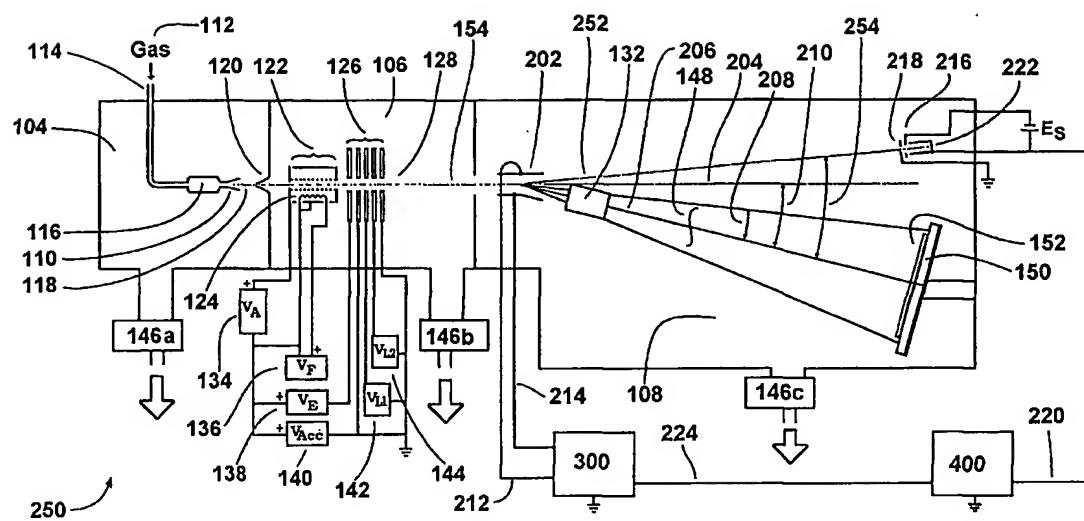
Figure 7
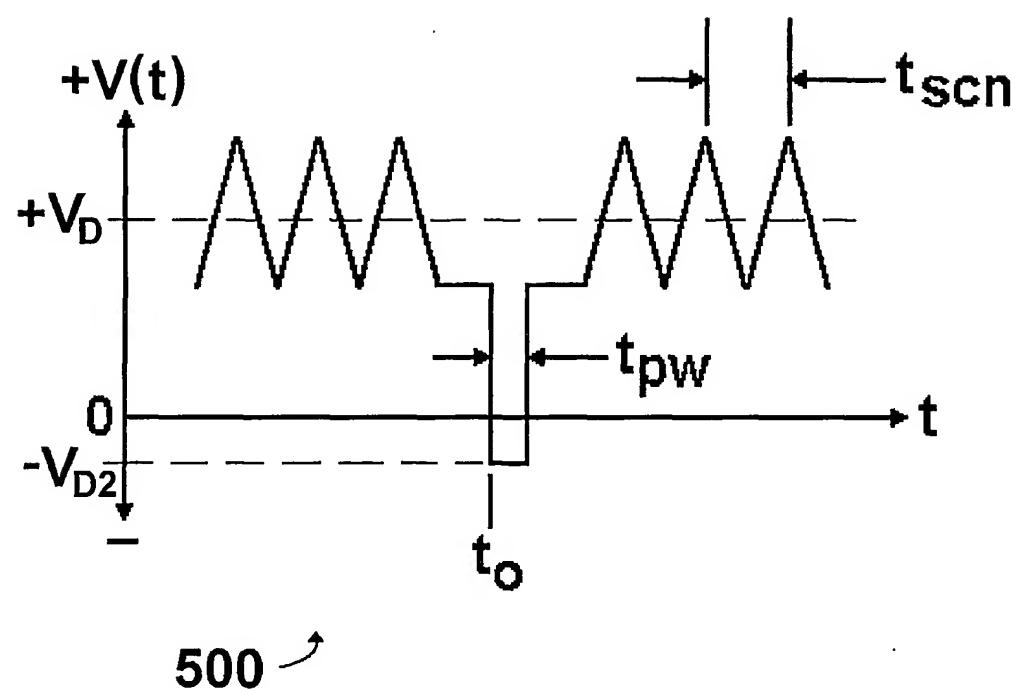
Figure 8

INTERNATIONAL SEARCH REPORT

A.   CLASSIFICATION OF SUBJECT MATTER

IPC(7)   :C23C 14/00
US CL   :204/192.2

According to International Patent Classification (IPC) or to both national classification and IPC

B.   FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   204/192.2, 427/249, 204/192.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C.   DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,814,194 A (DEGUCHI et al) 29 September 1998 (29.09.1998), Fig. 1.	1-16
X,P	US 6,207,282 B1 (DEGUCHI et al) 27 March 2001 (27.03.2001), Fig. 2.	1-15

☐   Further documents are listed in the continuation of Box C.   ☐   See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	
"O"	document referring to an oral disclosure, use, exhibition or other means	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
06 SEPTEMBER 2001	3 0 OCT 2001

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	DAVID VANORE
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